Feasibility Studies for the PANDA Experiment at FAIR

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FEASIBILITY STUDIES FOR THE $\overline{\text{P}}$ANDA EXPERIMENT AT FAIR*

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$\overline{\text{P}}$ANDA, the detector to study AntiProton ANnihilations at DArmstadt, will be installed at the future international Facility for Anti-proton and Ion Research (FAIR) in Darmstadt, Germany. The $\overline{\text{P}}$ANDA physics program is oriented towards the studies of the strong interaction and hadron structure performed with the highest quality beam of anti-protons [1]. In the preparation for $\overline{\text{P}}$ANDA experiments, large-scale simulation studies are being performed to validate the performance of all individual detector components and to advice on detector optimisation. The feasibility of the analysis strategies together with the calibration methods are being studied. Simulations were carried out using the framework called `PandaROOT` [2], based on `ROOT` and the `Virtual Monte Carlo` concept [3].

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1. Introduction

With the $\overline{\text{P}}$ANDA physics program various questions related to the properties of the strong interaction will be answered. This experiment operates in the transition region between the perturbative and the non-perturbative QCD regimes and, thereby, will gain insight into the mechanism of hadron mass generation and quark confinement.

The highest quality beam of anti-protons, in terms of intensity and resolution, is the key ingredient for the $\overline{\text{P}}$ANDA project. The momentum range of anti-protons of 1.5–15 GeV/c gives access to a center-of-mass energy range from 2.2–5.5 GeV/c^2 in $\overline{p}p$ annihilations. The $\overline{\text{P}}$ANDA detector will measure precisely momenta and scattering angles of both charged and neutral particles of the reaction products to detect the complete spectrum of final states relevant for the $\overline{\text{P}}$ANDA physics cases.

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2. The PandaROOT framework

The offline software for $\overline{\mathrm{P}}$`ANDA`, `PandaROOT`, is an extension of the `FairROOT` [4] framework being designed for the FAIR project. The `PandaROOT` framework, being developed by the $\overline{\mathrm{P}}$`ANDA` Collaboration, is being used for both simulation and data analysis of the $\overline{\mathrm{P}}$`ANDA` physics studies. It contains tools adapted from high energy physics experiments, such as event generators, to produce the reaction of interest and its decay chain, to generate the background from $\overline{p}p$ annihilation or to study the $\overline{p}A$ collision. Also, various tools allowing to test the reconstruction algorithm, and the complete digitization and reconstruction chain, and allowing to perform a detailed analysis together with the full geometry model are included in this framework. `PandaROOT` is highly versatile and enables a user-friendly interface to various transport engines, like GEANT3, GEANT4 and Fluka [5].

3. The $\overline{\mathrm{P}}$ANDA setup

To enable a rich physics program with the $\overline{\mathrm{P}}$`ANDA` detector, all components have to be carefully designed and tuned. The $\overline{\mathrm{P}}$`ANDA` detector, with its components, is presented in Fig. 1 and consists of two parts, a Target Spectrometer (TS) and a Forward Spectrometer (FS). Precise tracking and Particle IDentification (PID) are crucial to measure momenta of particles with a good detection efficiency. This is achieved by exploiting a Micro-Vertex-Detector (MVD), Straw Tube Tracker (STT) or, alternatively Time Projection Chamber (TPC), six Drift Chambers (DC), a muon and Cherenkov (DIRC Detection of Internally Reflected Cherenkov) detectors, marked in Fig. 1. The high resolution Electro Magnetic Calorimeter (EMC) in the TS and the FS is

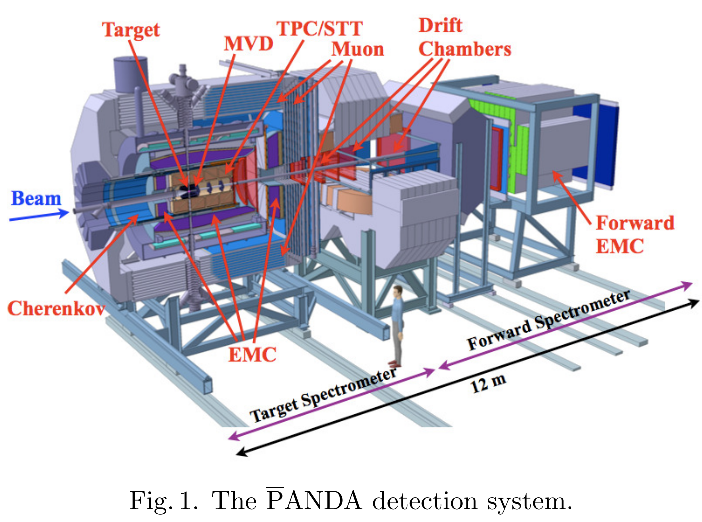


Fig. 1. The $\overline{\mathrm{P}}$ANDA detection system.

particular important to detect photons in a very broad energy range, starting from a few tens of MeV up to several GeV, as expected in the reactions aimed for $\overline{\text{P}}$ANDA. All sub-detectors together will cover nearly the full solid angle. A very high precision anti-proton beam, $\Delta p/p \sim 10^{-4}$–10^{-5}, together with a high luminosity, $L \sim 10^{31}$–$10^{32}\,\text{cm}^{-2}\text{s}^{-1}$, allow to measure very narrow, 50–100 keV, mass states of charmonium and reactions with cross-sections down to in the order of pb. The main requirements addressed to the tracking devices are a good momentum resolution at the percent level and the ability to handle high count rates. The MVD is the detector closest to the interaction point. This tracking device for charged particles is essential for a very precise determination of secondary decay vertices of short-lived particles. A spatial resolution below 100 μm is required and simulations show that 11 μm can be achieved [1]. The MVD is surrounded by the STT or the TPC, which will be used for a main track reconstruction. The position resolution in x and y coordinates of about 150 μm and the resolution of 3 mm in z direction is expected. The TPC or the STT will be combined with the subsystem consisting of Gas Electron Multiplier (GEM) detectors to perform tracking in the FS at angles below 22°. The GEMs have rate capabilities thousand times larger than achievable with drift chambers, therefore they can handle a higher flux of particles. The generator for background reactions (DPM [6]) was used to generate events at the momentum of 3.6 GeV/c and the reconstructed paths from the MVD combined with the TPC tracks are presented in Fig. 2(a). This graph shows a very good matching of track segments coming from these two detectors. One of the systems used for PID in $\overline{\text{P}}$ANDA is the DIRC detector, used for identifying particles with momenta above 1 GeV/c. The velocity information determined from the Cherenkov

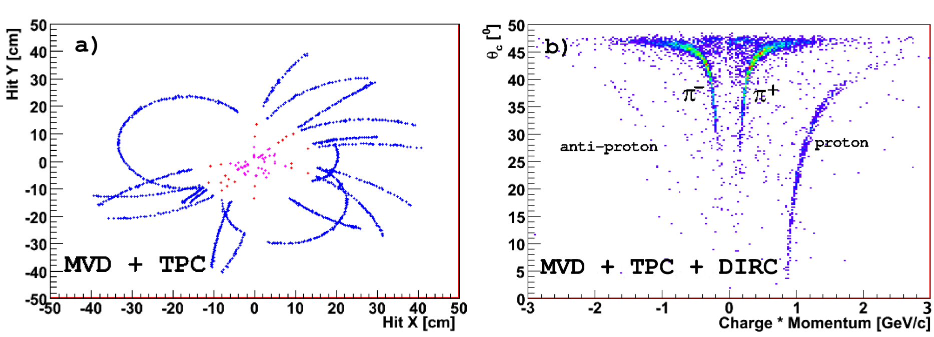


Fig. 2. (a) Reconstructed tracks of charged particles from track segments in MVD (dots in the middle) and TPC (outer curves) detectors. (b) Identification of charged particles with different momenta and charge using the MVD, TPC and DIRC detectors. The Y axis represents the Cherenkov angle Θ. Plots are taken from S. Spataro, INFN Torino.

angle $\Theta = \arccos(1/n\beta)$ of a charged particle, propagating in the medium with the refractive index n, is combined with the momentum information from the tracking detectors. Fig. 2(b) presents the identification of 10^4 particles generated with the DPM and reconstructed by the MVD, TPC and DIRC detectors. A very good separation of charged particles, π^+, π^- and protons, has been shown. The EMC detector, Fig. 3(a), is mainly used for photon detection, but it also measures the deposited energy of electrons, positrons, muons and hadrons. Muons and hadrons lose only a certain fraction of their kinetic energy by ionisation processes, while e^- and e^+ deposit their complete energy in the electromagnetic shower. This information can be used for PID as illustrated in Fig. 3(b). The $\overline{\text{P}}$ANDA physics program relies heavily on the capability to measure photons with high energy, position and, partly, time resolutions over a wide dynamic range. Thus, a highly granular EMC detector will be employed with fast PWO scintillators having a short radiation length, $X_0 = 0.89$ cm, a high energy resolution for photons and electrons, $1.5\%/\sqrt{E(\text{GeV})} + 1.3\%$, and a very good time resolution, < 1 ns for deposited energy above 80 MeV, obtained from a measurement with a realistic prototype equipped with a 1 cm^2 Avalanche Photo Diode (APD) and Sampling ADC readout [7]. In the final configuration the PWO crystals will be equipped with two APDs of 1 cm^2 size each, thus gaining an improvement factor up to $\sqrt{2}$ for the energy and time resolution. Such photon detectors are needed to cope with high count rates and with the proposed compact design of the TS.

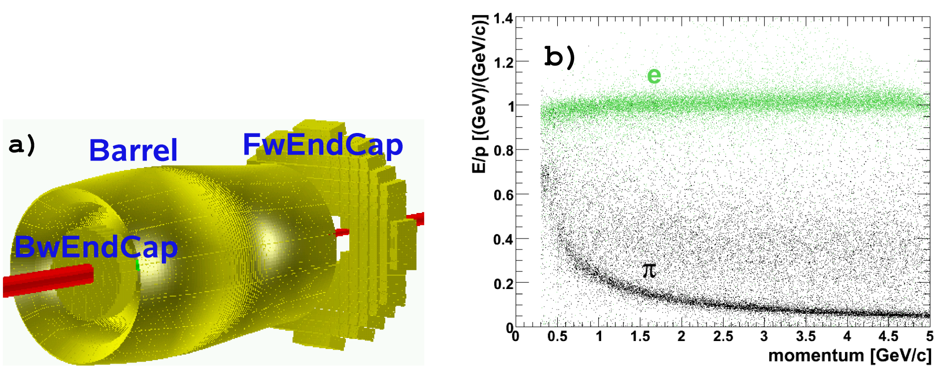


Fig. 3. (a) A 3D view of the electromagnetic calorimeter in the target spectrometer of $\overline{\text{P}}$ANDA. The barrel EMC (Barrel) and both, forward (FwEndCap) and backward (BwEndCap) EMC end-caps are shown. (b) E/p *versus* track momentum for electrons and pions in the momentum range between 0.3 GeV/c and 5 GeV/c.

4. The charmonium h_c (1^1P_1) reconstruction

The invariant mass reconstruction requires a precise determination of the energy deposited by photons and the opening angle between them, which can be achieved only by a highly granulated calorimeter; the $\overline{\text{P}}$ANDA EMC fulfils this requirement. The EMC plays a crucial role in the reconstruction of the singlet (1^1P_1) state of charmonium, h_c, presented below. The following decay mode of the h_c:

$$\overline{p} + p \to h_c \to \eta_c + \gamma \to \left(\pi^0 + \pi^0 + \eta\right) + \gamma \to 7\gamma \tag{1}$$

has been studied in this work. The chain (1) was generated with the EvtGen generator and the invariant mass analysis was done using the Rho package [1]. The two-photon invariant-mass spectra, reconstructed from combinations of seven photons in the final state are presented in Fig. 4. Peaks which stem from π^0 and η masses are found on top of a combinatorial background. A Gaussian function, describing the signal convoluted with a second-order polynomial, describing the background, was fitted. Cuts with a window of 3σ around the π^0 and η mass peaks were applied in a further analysis and the background was reduced significantly. With these cuts, a clean η_c invariant mass spectrum was extracted to finally identify the h_c state, as demonstrated in Fig. 5. The h_c reconstruction efficiency, $\varepsilon_{\text{Reco}}$, obtained from the presented analysis was found to be 26%. The expected number of events to be measured during the $\overline{\text{P}}$ANDA experiment was estimated taking into account the production cross-section, σ_p, which was calculated from the Breit–Wigner formula at the resonance energy for the process: $\overline{p}p \to h_c \to \eta_c + \gamma$ [1]. Also, the total branching ratio for the process $\eta_c \to \pi^0\pi^0\eta$, $\text{BR}_{\text{tot}}^{\eta_c\to\pi^0\pi^0\eta}$, was used. In the table on the right hand site of

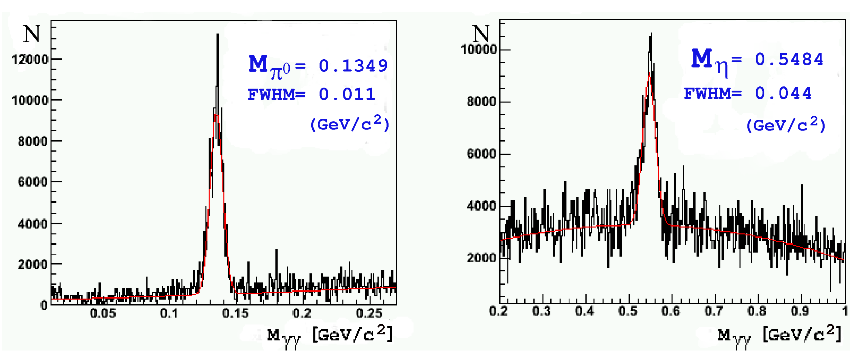
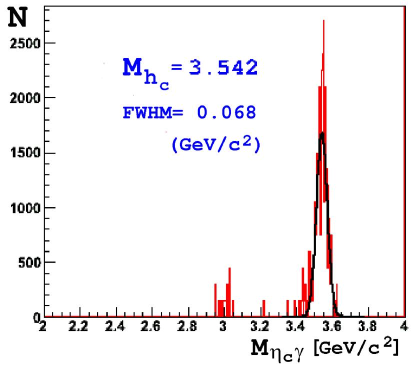


Fig. 4. The two-photon invariant mass spectra reconstructed in the EMC detector from combinations of seven photons in the final state from chain (1). A Gaussian fit combined with a second-order polynomial is shown.



	Parameters	Events per day
σ_p	33 [nb]	
$\mathrm{BR}_{\mathrm{tot}}^{\eta_c\to\pi^0\pi^0\eta}$	6.153×10^{-3}	
$\varepsilon_{\mathrm{Reco}}$	26 [%]	
t	1 [day]	
L^{HL}	2×10^{32} [cm^{-2}s^{-1}]	931
L^{HR}	10^{31} [cm^{-2}s^{-1}]	47

Fig. 5. Left: $\eta_c\gamma$ invariant mass reconstructed after 3σ window cuts on π^0, η and η_c masses. Right: Parameters used to calculate the collected number of events per day, expected to reveal the signal of charmonium h_c. The calculated numbers of measured events/day are presented in the lower part of the table.

Fig. 5 the most important ingredients, which were used in the analysis, are summarized. The calculation was done for two modes available for $\overline{\mathrm{P}}$ANDA: the high luminosity mode, L^{HL}, with $\sigma_p/p\sim10^{-4}$, and the high resolution mode, L^{HR}, with $\sigma_p/p\leq4\times10^{-5}$ and the estimated numbers of collected events/day are presented in that table. The obtained numbers are by factors of 5 and 10 larger for L^{HR} and L^{HL}, respectively, than for other decay modes of the charmonium h_c state, such as $h_c\to\eta_c\gamma\to\Phi\Phi\gamma$ (2), described in [1]. This is mainly due to the total branching ratio $\mathrm{BR}_{\mathrm{tot}}^{\eta_c\to\pi^0\pi^0\eta}=6.153\times10^{-3}$, which is one order of magnitude larger than the total branching ratio of $\mathrm{BR}_{\mathrm{tot}}^{\eta_c\to\Phi\Phi}=6.24\times10^{-4}$. The disadvantage might be an insufficient background suppression of the decay channel (1) compared to the channel (2). A complete background analysis of the competing channels as $\overline{p}p\to\pi^0\pi^0\pi^0$ and $\overline{p}p\to\pi^0\pi^0\eta$ is ongoing.

5. Summary and conclusions

With the $\overline{\mathrm{P}}$ANDA detector a broad range of physics studies will be covered. The precise measurement of the momentum and position of a particle will be possible using highly tuned tracking, PID and EMC sub-detectors. The 1^1P_1 state of charmonium is one of several benchmark channels studied for $\overline{\mathrm{P}}$ANDA, where masses and widths will be measured precisely. Recently, the h_c was studied in e^+e^- experiments (CLEO-c [8], BES3 [9]), but so-far only an upper limit for the total width, $\Gamma<1$ MeV, has been published. In the $\overline{p}p$ annihilation experiment, such as $\overline{\mathrm{P}}$ANDA, the exact value of Γ will be measured. In this work we analysed the decay of the $h_c\to\eta_c\gamma\to\pi^0\pi^0\eta$. Preliminary studies show that the observation of this channel is feasible and further investigations of its background are under way.

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